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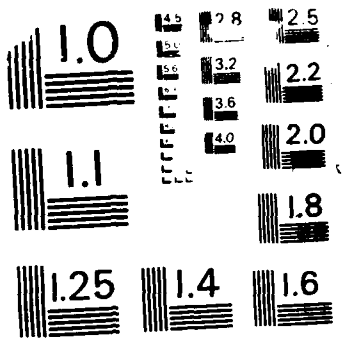

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The investigations of non-steady and unstable combustion in a dump combustor have been completed. The large amplitude driving mechanism centers on the periodic formation and combustion of a large vortex, the phase of heat release being governed by both gas dynamic and chemical delay times. This mechanism is now very well understood, both in principle and in quantitative detail. These results make it a prime candidate for investigations into active control of unstable combustion.

The unsteady combustion facility is now being modified to study the details of combustion processes in large vortices utilizing a CID image intensified camera and an LDV for velocity measurements in the hot gas. This study constitutes an essential element in a larger study of shock enhancement for combustion of hydrogen in supersonic burners.

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1. RESEARCH OBJECTIVES

(a) Combustion Instability

Over the past five years we have studied the detailed mechanism of combustion instability in a simple dump combustor. Our determination to understand the mechanism, rather than the symptoms, was driven not only by the fact that other such studies seldom if ever get to the mechanism but, toward the completion of the work, by the requirement to show that efficient and simple control of non-linear instability requires a knowledge of the mechanism.

The effort this year was devoted i) complete studies of chemical time delay and ii) to carry out spatial heat release-pressure correlations showing the manner in which the processes within the entire chamber developed into the limit cycle. The first constituted the completion of work, a portion of which was reported last year. The second was a new and extensive set of measurements which were of particular interest in demonstrating the essential non-linearity of the mechanism.

This will complete our work on the mechanism of combustion instability; any further work will deal with the control of combustion instability and will be the subject of a new proposal.

(b) Experiments on Combustion in Large Vortices

The primary thrust of this grant concerns a detailed study into the combustion process of large vortices. It is closely related to our extensive effort on the possibilities of shock enhancement of mixing and combustion of hydrogen with air.

The principal effort this year has been to design and build a new combustion chamber which will allow the production of large vortices in a well-controlled periodic manner and over a wide and controllable range of frequencies. At the same time, we are making major improvements in the data acquisition system, centering about a CID array camera with image intensification and an LDV for the purpose of making detailed velocity measurements in the hot gas.

(c) Theoretical Studies of Vortex Combustion

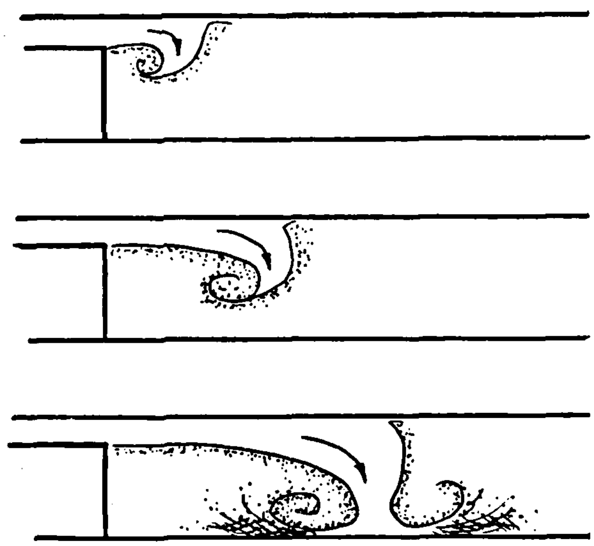
The theoretical investigation of flames distorted by vortex structures was initiated under this grant some years ago and has proven to be an extremely informative, as well as popular, direction of research. With regard to the present program, the aim of these investigations is both to provide interpretation of the experiments and to develop laws that allow scaling the results to different parametric ranges. The work this year yielded important information concerning the mixing and chemical reaction when the viscous effects were large enough to retard the deformation of the flame and hence to decrease the overall combustion rate. A new dimensional quantity, the ratio flame sheet spreading to viscous diffusion, was introduced as a measure of this phenomenon.

2. STATUS OF RESEARCH

(a) <u>Combustion Instability</u>

An investigation of the mechanism leading to growth and sustenance of large pressure oscillations in a laboratory combustor has been completed. This work has shown that relatively low frequency oscillations can be produced in airbreathing systems of reasonable size and that these oscillations are associated with longitudinal acoustic modes of the entire combustion duct. The features of this mechanism have been made clear by this investigation and it is sufficiently understood that we can now develop methods for its suppression.

The mechanism which underlies the development and sustenance of the pressure oscillations contains the following elements. We consider a combustor supplied with a fuel-air mixture in which the flame is stabilized on a rearward facing step as shown in Fig. 1. The mechanism is the same for systems in which bluff body flame holders such as "V" gutters are used.



1. Combustion Oscillations on Rearward Facing Step.

Pressure oscillations at one of the longitudinal acoustic modes of the system produce velocity and pressure fluctuations at the flame holder lip which periodically trigger the formation of large vortices in the recirculation zone downstream of the flameholder. The vortices grow as they move downstream and, after a fluid dynamic time delay If, their interaction with the lower wall produces an increased mixing between the unburnt mixture and the completely burnt gas in the recirculations zone. After a further time delay or chemical induction time Ic, which is fixed primarily by chemcial parameters, this increase in mixing rate will produce an increase in the heat release rate.

When the total delay time, If + Ic, has the appropriate magnitude with respect to the period of the oscillation, this fluctuation in the heat release will drive the pressure oscillation. If, however, the total delay is too long, the fluctuation will extract energy from the acoustic field and the pressure oscillations will decay.

This picture is over simplified primarily becasue the heat addition fluctuation occurs over a period which is comparable to that of the oscillation and is spread out over the whole combustion chamber. Hence, to discern the overall effect of the oscillation, it is necessary to use a representation of the Rayleigh criterion which involves an integral over a whole period of the oscillation and which extends over the entire volume in which heat is added to the gas stream.

Frequency Estimates- The acoustic modes are determined by the longitudinal geometry of the entire system including the supply chambers as well as the combustor. A one-dimensional acoustic analysis of the system has been used to determine the natural frequencies and the corresponding mode shapes. These have been compared to the experimental frequencies of oscillation and the experimental pressure mode shapes when operating conditions yield large pressure oscillations. The frequencies agree quite well with the experiment and the theory predicts the location of modal nodes and the mode shapes fairly accurately. The frequency of oscillation depends in a predictable manner upon the geometry of the flameholder, the mean flow speed, the fuel type, and the equivalence ratio.

Influence of Chemical Parameters- During the past year, a parametric study was performed to investigate the dependence of the vortex shedding frequency upon variations in the mean flow speed and equivalence ratio for a fixed geometry and fuel type. The results reveal that small changes in equivalence ratio can lead to excitation of acoustic modes of greatly varying frequency. Thus, the chemical induction time was determined to be important even in low frequency instabilities.

The chemical time dependence on the parameters of the system is consistent with the model described above. For example, the model indicates that shorter time delays allow the mechanism to support higher frequency oscillations. The chemical induction time is decreased as the fuel-air ratio approaches the stoichiometric value or when the fraction of hydrogen in the methane-hydrogen fuel mixture is increased. In agreement with these expectations, we observe in the experiments that high frequency modes can be excited when we use fuel-air ratios near stoichiometric but not for lean or rich mixtures. Similarly, when fuels which contain high fractions of hydrogen are used, high frequency modes are excited.

Fluid Dynamic Parameters- Reduction of the step height results in the excitation of higher frequency modes as we expect because the fluid dynamic delay time is reduced. In addition this result supports the view that the influence of mixing as the vortex structure impinges on the lower wall of the combustor is important for most instabilities observed.

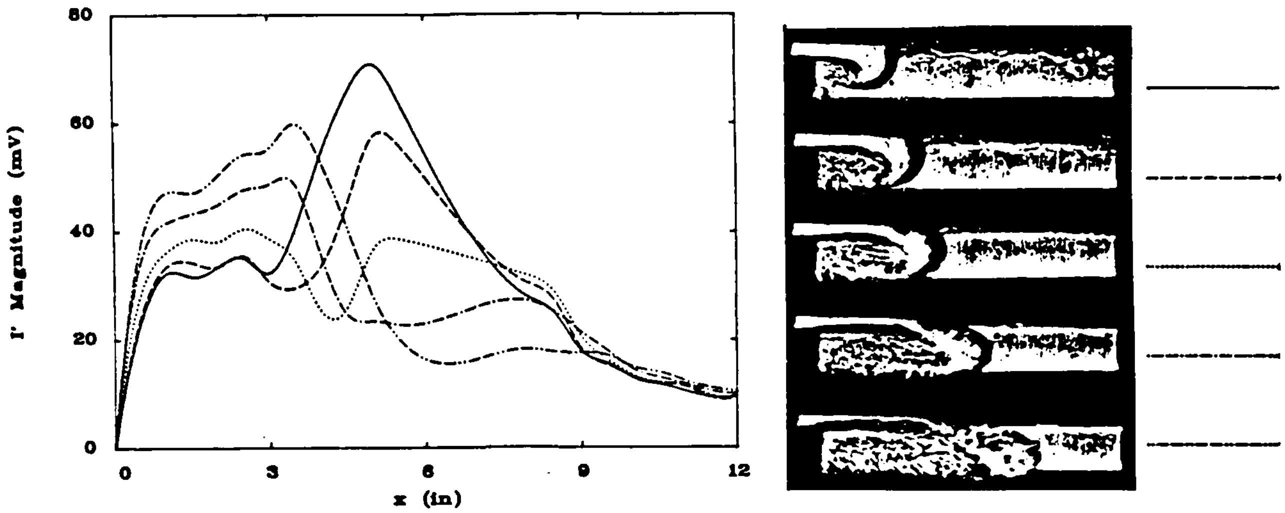
We have also found experimentally that pressure amplitudes increase when the frequency of the osciallations increases; this result is in agreement with the calcualtions carried out in this program by Hendricks who showed that the fluid dynamic time delay decreased almost lineraly with the amplitude of the pressure fluctuation.

Finally, higher frequency modes are observed at higher mean flow speeds. This effect is not well understood but may be caused by decreases in the mixture fraction of cold reactants at high speeds resulting in a shorter chemical reaction time.

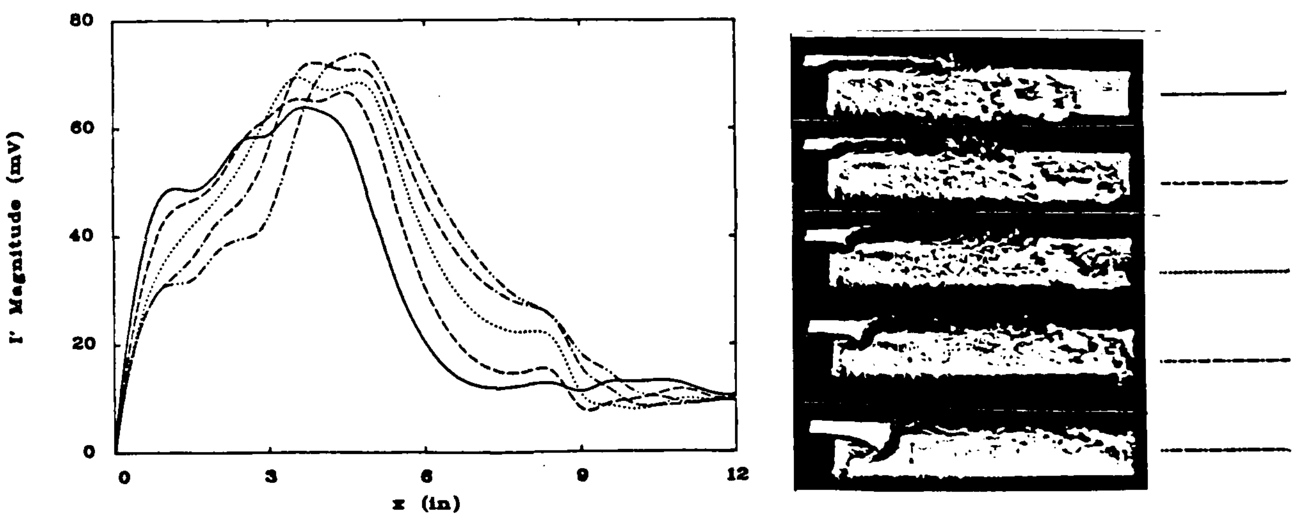
Stability Criteria- One of the primary results of the research carried out during the past year was the collection of complete sets of light intensity and pressure fluctuations data for the whole duct and for a number of different configurations of the system. The light intensity data are used to determine the heat addition fluctuations, and these, in conjunction with pressure fluctuation data, have been used to determine the input of energy to an acoustic mode by the heat addition process.

Comparison of frames from shadowgraph movies with measured values of the instantaneous distributions of the radiation intensity in the combustion chamber during combustion instability reveal that the volumetric rate of heat release due to combustion in the regions near the flameholder continue to rise long after the large vortex structure passes. At locations farther down stream, the amplitude of the fluctuating radiation intensity signal is larger and the peak in reaction occurs only shortly after the vortex passes. Thus, an apparent combustion wave is produced in the duct by the passage of the vortex and the front of this wave moves at a nearly constant velocity that is about twice the mean flow speed for standard operating conditions. The accelerating vortex structure, on the other hand, was found to move at about half the mean flow speed measured at the flameholder lip.

Data for the distribution of combustion intensity versus distance downstream form the flame holder are shown in Fig. 2, 3 for eight different times during a complete cycle; corresponding shadowgraph photographs for same time intervals are also shown. The combustion wave described above is clearly visible.



2. Vortex Shedding at 188 Hz; First Half-Cycle



3. Vortex Shedding at 188 hz; Second Half-Cycle

The role of Rayleigh's Criterion was examined in detail as the predominant process driving and damping instabilities of combustion chambers. Energy considerations show that the potential for augmentating the acoustic field by coupling of pressure fluctuations and heat release rate fluctuations is about two orders of magnitude greater than other energy transfer mechanisms. This observation suggested measuring phase difference between the fluctuating pressure and the oscillatory radiation intensity signal at locations throughout the combustion chamber for several example operating conditions.

The results indicate that regions of strong damping generally occur immediately upstream of the location at which the amplitude of the radiation intensity is a peak. Similarly, regions of strong damping of the acoustic energy usually occur just downstream of this location. Thus, the location of the largest heat release occurs at a time during the pressure oscillation that results in no driving or damping of the acoustic field after a finite limit cycle has been reached.

Modelling the feedback mechanism to determine the phase difference between the pressure and the heat release oscillations traditionally uses a pressure-sensitive time delay to predict linear stability characteristics. This has given considerable success for liquid-propellant and solid-propellant systems. However, for combustion systems in which the flame is stabilized in a recirculation zone, the feedback mechanism associated with vortex shedding phenomena is sensitive to the velocity fluctuations at the flameholder.

A linear stability model based on a velocity-sensitive time lag is used for the geometry of the laboratory combustor. The combustion is modelled by a volumetric source downstream of the flameholder whose amplitude is related to the amplitude of the velocity fluctuations over the flameholder and whose phase lags the same velocity by some time delay. The solution method requires that particular values of the time delay and the interaction index determine the amplification rate and frequency of the oscillation. For feedback within one cycle of oscillation the time delay required for instability is generally shorter for higher frequencies. Large changes in the phase difference between the pressure fluctuation and the velocity fluctuations occur near natural frequencies of the system. This has a strong influence on the stability boundaries predicted for the system.

Finally, possible mechanisms of nonlinear growth are described within the framework of this model. Experimental results for particular operating conditions reveal that a combination of mechanisms that are discussed may be responsible for limit cycle behavior. Experimental results show that the amplitudes of high frequency modes are generally larger than the amplitudes of low frequency modes and that the frequency of oscillation is usually higher than predicted. These results suggest a nonlinear evolution that involves an increase in the frequency of oscillation and a decrease in the time delay parameter as the amplitude of the oscillation reaches a finite-limiting amplitude.

(b) Experiments on Combustion in Large Vortices

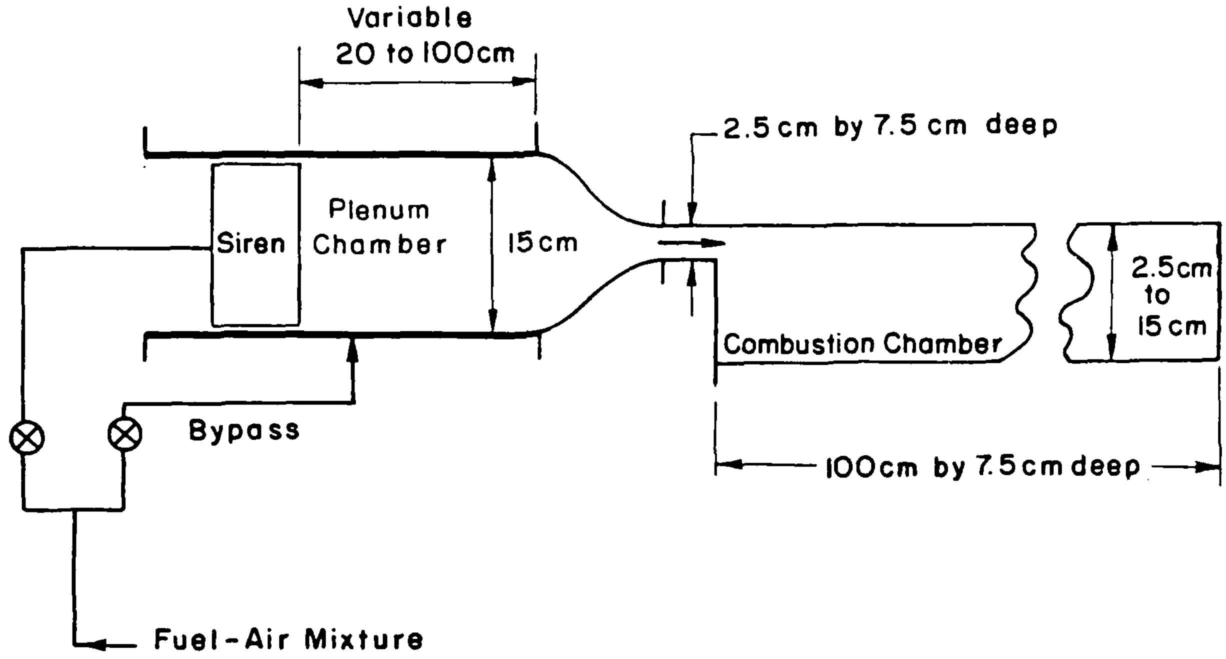
The primary work carried out under this grant has been the design and construction of a new test duct for the proposed experiments. Our aim was to develop an apparatus in which we could produce vortices at the interface between burnt gas and a fresh fuel air mixture and to observe the influence of various fluid dynamic and chemical parameters on the rate of combustion in these vortices.

One of the parameters we want to observe is the light emitted during the combustion process which is a good measure of the local volumetric heat release by the combustion process. We shall do this with a camera based on a charge injected device which has an array of 380 by 240 pixels and employs a gated image intensification system which is requried to sense the low light levels produced by the combustion of methane and air. This system will allow us to observe a region of about 15 cm by 24 cm with useful resolution it requires about 100,000 data points per picture. The data acquisition rate required to follow the developement of a vortex with this camera is over 100 million per second and is larger than our system can accomodate. Hence, we shall observe a periodic sequence of vortices and use a phase averaging technique.

Based on our experience in the combustion instability experiment, we have chosen to use the same rearward facing step geometry to produce the vortices. However, we have modified the combustion duct so that we may control the frequency and growth rate of the vortices. In addition we have increased the depth of the test section so that the vortices can grow to a much larger scale before being influenced by the lower wall of the combustion chamber.

New Test Facility- A schematic diagram of the new test facility is shown in Fig.4. The most evident change in the combustion chamber is the use of a duct with a height that can be varied bewtween 2.5 and 15 cm. The maximum depth will allow vortices to reach scales of 10 cm before the inteference effects of the lower wall becomes important.

In the previous experiments, the frequency of the oscillation selected by the instability was one of the acoustic modes of the system and the mode selected was a complex function of the length of the plenuim chamber, the geometry of the rest of the system and the chemical parameters of the fuel-air mixture. In the present apparatus, we will use this result to our advantage by controlling the length of the plenum chamber to fix the frequency of one of the acoustic modes to match the desired frequency. We gain further control over the frequency of the vortex shedding by using a siren, placed at the upstream end of the combustion chamber, to excite the duct at the desired frequency. The amplitude of the energy supplied by the siren to the desired mode can be varied by passing part of the fuel-air mixture through the siren and part through a bypass around the siren.



4. Diagram of New Experimental Facility

This system will allow us to control the amplitude and frequency of the velocity and pressure fluctuations at the flame holder lip. Thus, we will be able to control the frequency of vortex shedding from the lip. Futher, our previous work has shown that the rate of growth of the vortices is a function of the amplitude of the fluctuations at the flame holder lip. The bypass arrangement which we have provided for mixture injection allows us active control of the amplitude as well as the frequency of the fluctuations and thereby control the rate of growth of the vortices. The apparatus will produce vortices at frequencies between 100 to 600 Hz and will allow us to observe vortices with scales up to 15 cm. Construction has been completed and initial tests are in preparation.

Instrumentation- The primary new item of instrumentation is the gated image intensified CID camera which will be used to measure the light emitted by the combustion process and thus to estimate the rate of heat release throughout the vortex. Photographs will be obtained at a frequency of 30 frames per second and will be stored an a VCR. Later, individual frames will be selected from this video movie with a frame grabber and the intensity data will be digitized for further analysis.

In addition, we will use a new LDV system to measure one or two velocity components throughout the flow field. This Disa system with a single velocity component capability was acquired during the 1986-87 contract year and the two component system will be completed early in the 1987-88 contract year.

Other parameters measured will include: the velocity fluctutation at the flame holder lip, obtained with a conventional hot wire system; pressure and pressure fluctuations on one wall of the duct; single frame shadowgraph pictures; and 8,000 frames per second shadowgraph movies. Finally, we have developed an ion probe which will allow us to determine the ion density in a volume of gas corresponding to a 1 millimeter cube. Because the regions where combustion is taking place are also regions in which the gas is highly ionized, this insturment will be used in conjunction with the flow visualization techniques to make certain that we can define the regions of active combustion accurately.

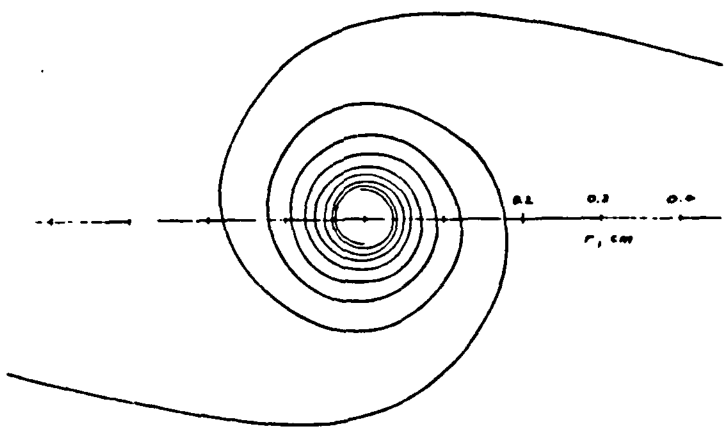
(c) Theoretical Studies of Vortex Combustion

Vortex Kinematics- Consider the interface between a reactant in the upper half plane of initial concentration $\kappa_1 = 1$ and a different reactant in the lower half plane of initial concentration $\kappa_2 = 1$. At the time $t = 0$ a viscous point vortex is established at the origin; the velocity components associated with this vortex are

$$v_r = 0 \tag{1}$$

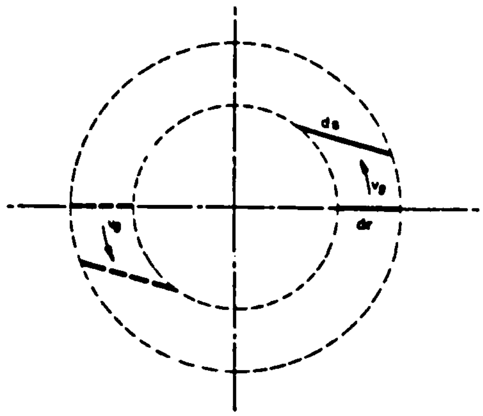
$$v_\vartheta = \frac{\Gamma}{2\pi r}\left(1 - e^{r^2/4\nu t}\right) \tag{2}$$

where Γ is the circulation of the vortex and ν is the kinematic viscosity which we take to be the same for both pure species as well as for the product. As a result of this velocity field, the original interface between the two reactants is "wound up" into spirals, Fig. 5, which become more closely spaced as the time increases and as the circulation is increased.

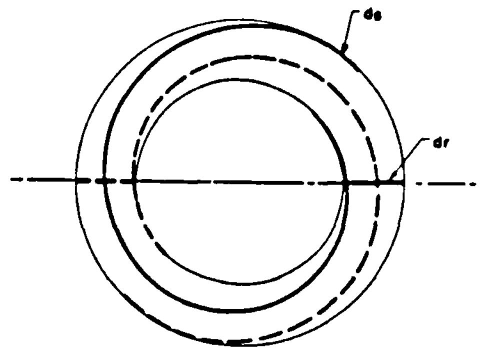


5. Distorted Contour of Interface Between Two Reactants

Because the radial velocity component vanishes, fluid elements move along circular paths about the origin. the element of fluid interface initially coincident with the horizontal axis moves



6. Strain and Rotation of Element Initially on Horizontal Axis



7. Two Interfacial Contours Developed Within Annulus

between two concentric circles, Fig.6. The element makes an angle ψ with respect to the local tangent to the circle and

$$-r\frac{\partial\vartheta}{\partial r} = \operatorname{ctn}\psi \equiv \Lambda \qquad 3$$

By integrating v_θ/r, from Eq. 2, we obtain the remarkably simple result

$$\Lambda = 2v_\vartheta t/r \qquad 4$$

The length ds of the element of interface is

$$ds = \left\{1 + \left(\frac{r\partial\theta}{\partial r}\right)^2\right\}^{1/2} dr = (1+\Lambda^2)^{1/2}\, dr \qquad 5$$

The motion reduces ψ with time, the interface is continuously being stretched along its length, and at some time later makes a complete loop about the origin, Fig. 7. When these spirals are closely spaced, this angle is nearly constant and Eq. 5 may be integrated about a complete circle giving

$$2\pi r = (1+\Lambda^2)^{1/2}(r_2-r_1) \qquad 6$$

where $r_2 - r_1$ is the radial extent of the circular annulus in which the angle of the deformed interface is ψ. In actuality this strip contains two interfacial elements, Fig. 4, one originating on the right horizontal axis, the other on the left. One may interpret

Eq. 6 as giving the width of an annulus containing a single stretched line element circling the origin,

$$\Delta r = \pi r / (1+\Lambda^2)^{1/2} \qquad 7$$

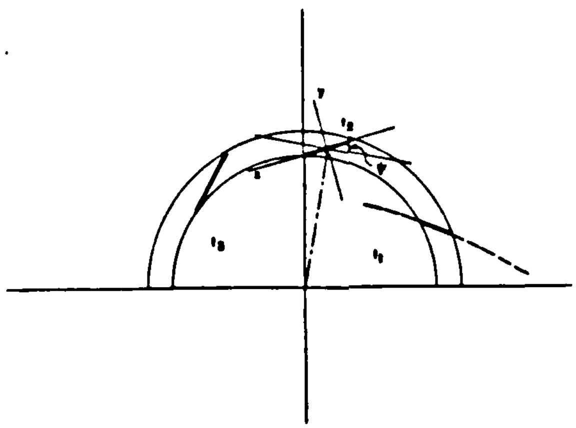
It is convenient to construct a local coordinate system, Fig.8, and to express the local flow field in these coordinates. The local x and y velocity components are

$$u = \left\{ (\tfrac{1}{2}\sin 2\psi) x + (\cos 2\psi) y \right\} \partial\Lambda/\partial t \qquad 8$$

$$v = -(\tfrac{1}{2}\sin 2\psi) y \; \partial\Lambda/\partial t \qquad 9$$

The interface is always alligned with the moving x - axis and hence the straining rate along the interface is

$$\varepsilon \equiv \frac{\partial u}{\partial x} = (\tfrac{1}{2}\sin 2\psi)\,\partial\Lambda/\partial t = \Lambda/(1+\Lambda^2)^{1/2}\;\partial\Lambda/\partial t \qquad 10$$



8 Coordinate System for Local Analysis

<u>Fast Chemistry in a Vortex Field</u>- By "fast chemical reaction rates" it is implied that the two reactants cannot coexist on the time scale of interest in the problem. Physically, this requires that the chemical time be short in comparison to the time associated with diffusive mixing. This feature introduces two significant features into the analysis: i) There is neglegible effect of remote strips of reactant upon the one under consideration, and ii) the process is complete in a given strip when the reactants are consumed, which occurs in a finite time.

For the local analysis, therefore, it is sufficient to consider a single in an infinite plane domain with K_1 initially in the upper half-plane and K_2 in the lower half-plane. As time progresses, the two reactants diffuse toward their interface, at which K_1 and K_2 both vanish because of fast chemistry, and react in their stoichiometric ratio to produce the product. The product, in turn, diffuses back into the upper and lower half-planes. If there were no strain rate, the reactant distribution would be

$$K_1, K_2 = \pm \operatorname{erf}\left\{ y/(4Dt)^{1/2} \right. \qquad 11$$

where a stoichiometric ratio of unity has been assumed. The rate at which the reactant K_1 is consumed at the reaction interface is

$$D \frac{\partial K_1}{\partial y}(0,t) = (D/\pi t)^{1/2} \qquad 12$$

On the other hand, when the local interfacial region is being strained, the diffusion equation takes a more complex form. The appropriate solution for K_1 is then

$$K_1 = \operatorname{erf}\left\{ \bar{y}/(4D\mathcal{T})^{1/2} \right\} \qquad 13$$

and the consumption rate of reactant 1 per unit area of interface is

$$\left(\frac{D}{\pi \mathcal{T}}\right)^{\frac{1}{2}} \exp \int_0^t \varepsilon(t)\,dt \qquad 14$$

Recalling Eq. 10 giving the strain rate $\varepsilon(t)$ in the vortex, the rate at which the reactant K_1 is being consumed per unit area of interface is

$$\dot{V} = \left(\frac{D}{\pi}\right)^{\frac{1}{2}} \left\{ \int_0^t (1+\lambda^2)\,dt \right\}^{-1/2} (1+\lambda^2)^{1/2} \qquad 15$$

Now an element of interface originally of length dr has been stretched into a length ds, Eq. 5, an hence the reactant consumption rate by this element is

$$\dot{V}(r,t)ds = (D/\pi)^{1/2}\left\{\int_0^t (1+\lambda^2)dt\right\}^{-1/2}(1+\lambda^2)\,dr \qquad 16$$

In the unreacted state an annulus $2\pi r dr$ contains half reactant 1 with concentration $\kappa_1 = 1$, and half by reactant 2 with concentration $\kappa_2 = 1$. Moreover, as was pointed out in connection with Fig. 7, there are two interfaces within this annulus. Thus the reactant consumption rate, Eq. 16, integrated over time, will at some time t_* consume all of the reactant 1 within the annulus. Expressed analytically,

$$2\int_0^{t_*}\left(\dot{V}(r,t)ds\right)dt = \pi r dr \qquad 17$$

This relation may be written in detail using Eq. 16. The resulting expression may be cast in the form

$$\int_0^{\beta_*/\mu_a} (I(\xi))^{-\frac{1}{2}}\left[\left(\frac{1}{2\pi R}\right)^2 + \xi^2\left(1-e^{-\frac{1}{4\pi\xi}}\right)^2\right]d\xi = \frac{\pi}{2}\mu_a^{3/2} \qquad 18$$

where

$$I(\xi) = \int_0^{\xi}\left\{\left(\frac{1}{2\pi R}\right)^2 + \xi^2\left(1-e^{-\frac{1}{4\pi\xi}}\right)^2\right\}d\xi \qquad 19$$

$$\beta_* \equiv \Gamma^{2/3}D^{1/3}t_*/\pi r^2 \qquad 20$$

and

$$\mu_a \equiv \Gamma^{2/3}D^{1/3}/\nu \qquad 21$$

Because β_* is a number $\beta_*(\mu_a, R)$, Eq. 18 gives the reacted core radius at any time t after the start of motion.

The result is independent of Reynolds number except for very large values of μ_a. The asymptotic behavior for large μ_a is

$$r_* / (\Gamma^{2/3} D^{1/3} t)^{1/2} = 0.509 \qquad 22$$

The corresponding result for low values of μ_a is

$$r_* / (\Gamma^{2/3} D^{1/3} t)^{1/2} = 0.057 \mu_a \qquad 23$$

This result for low values of μ_a is new and of importance under circumstances where the viscous diffusion and the diffusion due to distortion are of the same order of magnitude. In fact the new dimensionless ratio μ_a, given in Eq.21, represents the ratio of the rate of growth of the burned core radius to the rate of growth of the viscous core.

Notation-

D	Coefficient of molecular diffusion
dr	Interfacial element length before distortion
ds	Interfacial element length after distortion
I	Defined in Eq. 19
r, ϑ	Polar coordinates for vortex flow
r_*	Radius of burned core
R	Reynolds number of vortex, $\Gamma/2\pi\nu$
t	Time
t_*	Defined by Eq. 17
v_r, v_ϑ	Radial and tangential velocity components
$\dot{V}$	Reactant consumption rate per unit area of interface
x, y	Local cartesian coordinates of interfacial element
$\bar{y}$	$y(1+\Lambda^2)^{1/2}$
$\mathcal{T}$	$\int_0^t (1+\Lambda^2)\,dt$
β_*	Defined in Eq. 20
Γ	Circulation of vortex
ε	Element strain rate, Eq. 10
κ_1, κ_2	Concentration of Reactant 1 and 2 respectively
Λ	Defined by Eq. 4
μ_a	Ratio of diffusive spreading to viscous spreading, Eq. 21
ν	Kinematic viscosity
ψ	Angle of interfacial element, Eq. 3

3. PUBLICATIONS

Awad, E. and Culick, F. E. C. (1983), Existence and Stability of Limit Cycles for Pressure Oscillations in Combustion Chambers," AIAA Paper 83-0576 AIAA 21st Aerospace Sciences Meeting.

Awad, E. (1984), "Nonlinear Combustion Instabilities in Combustion Chambers," PhD Thesis, Karman Laboratory of Fluid Mechanics and Jet Propulsion, California Institute of Technology, Pasadena, CA.

Awad, E. and Culick, F. E. C. (1986), "On the Existence and Stability of Limit Cycles for Longitudinal Acoustic Modes in a Combustion Chamber," Combust. Sci. and Tech. 1986, Vol. 46, pp. 195-222.

Culick, F.E.C. (1987) "A Note on Rayleigh's Criterion," To appear in Combust. Sci. & Tech.

Crump, J. E., Schadow, K. C., Yang, V., and Culick, F. E. C. (1986), "Longitudinal Combustion Instabilities in Ramjet Engines: Identification of Acoustic Modes," J. Propulsion, V. 2, No. 2, pp. 105-109.

Hendricks, G. J. (1986), "Two Mechanisms of Vorticity Generation in Combusting Flow Fields," PhD Thesis, California Institute of Technology.

Humphrey, J. W. (1986), "Linear and Non-Linear Acoustics with Non-Uniform Entropy in Combustion Chambers," PhD Thesis, California Institute of Technology, Pasadena, CA.

Karagozian, A. R. (1982), "An Analytical Study of Diffusion Flames in Vortex Structures," PhD Thesis, Karman Laboratory of Fluid Mechanics and Jet Propulsion, California Institute of Technology, Pasadena, CA.

Karagozian, A. R. and Marble, F. E. (1985), "An Analytical Study of Diffusion Flames in Vortex Structures," International Combustion Institute, Western States Section, Pasadena, CA.

Karagozian, A. R. and Marble, F. E. (1986), "Study of a Diffusion Flame in a Stretched Vortex," Combust. Sci. and Tech., Vol. 45, pp. 65-84.

Marble F. E. (1985), "Growth of a Diffusion Flame in the Field of a Vortex," Recent Advances in Aerospace Sciences, . 395-413.

Marble, F. E. and Hendricks, G. J. (1986), "Structure and Behavior of Diffusion Flames in a Pressure Gradient," Twenty-First Symposium (International) on Combustion, Munich.

Marble, F. E.,Hendricks, G. J. & Zukoski, E. E. (1987), "Progress Toward Shock Enhancement of Mixing and Reaction in Supersonic Burners," AIAA Aerospace Sciences Meeting, San Diego, June, 1987.

Marble, F. E. (1987) "Diffusion, Mixing and Chemical Reaction of Liquids in the Field of a Vortex," Proceedings, Symposium on Chemical Reaction in Liquids, Chem. Soc. France. Paris, September 1987.

Norton, O. P. (1983), "The Effects of a Vortex Field on Flames with Finite Reaction Rates," PhD Thesis, Karman Laboratory of Fluid Mechanics and Jet Propulsion, California Institute of Technology, Pasadena, CA.

Smith, D. A. (1985), "Vortex Driven Combustion Instabilities Inside Ramjet Type Combustors," PhD Thesis, Karman Laboratory of Fluid Mechanics and Jet Propulsion, California Institute of Technology, Pasadena, CA.

Smith, D. A. and Zukoski, E. E. (1985), "Combustion Instability Sustained by Unsteady Vortex Combustion," AIAA/SAE/ASME/ASEE 21st Joint Propulsion Conference, Monterey, CA.

Sterling, J. D. and Zukoski, E. E. (1987), "Longitudinal Mode Combustion Instabilities in Air Breathing Engines," Paper No. AIAA-87-0220, AIAA 25th Aerospace Sciences Meeting.

Sterling, J. D. (1987) "Longitudinal Mode Combustion Instabilities in Air Breathing Engines," PhD Thesis, California Institute of Technology, Pasadena, California.

Yang, V. and Culick, F. E. C. (1983a), "Linear Theory of Pressure Oscillations in Liquid-Fueled Ramjet Engines," AIAA Paper 83-0574 AIAA 21st Aerospace Sciences Meeting.

Yang, V. and Culick, F. E. C. (1983b), "Linear Theory of Pressure Oscillations in Liquid Fueled Ramjet Engines," 1983 JANNAF Propulsion Meeting.

Yang, V. (1984a), "Pressure Oscillations in Liquid-Fueled Ramjet Engines," PhD Thesis, Karman Laboratory of Fluid Mechanics and Jet Propulsion, California Institute of Technology, Pasadena, CA.

Yang, V. and Culick, F. E. C. (1984b), "Numerical Calculations of Pressure Oscillations in a Side-Dump Ramjet Engine," AIAA Aerospace Sciences Meeting.

Yang, V. and Culick, F. E. C. (1985), "Analysis of Unsteady Inviscid Diffuser Flow with a Shock Wave," AIAA J. Propulsion and Power, V. 1, No. 3, pp. 222-228.

Yang, V. and Culick, F. E. C. (1986), "Nonlinear Analysis of Pressure Oscillations in Ramjet Engines," Paper No. 86-0001, AIAA 24th Aerospace Sciences Meeting.

4. PERSONNEL

Faculty

F. E. C. Culick
T. Kubota
F. E. Marble
E. E. Zukoski

Research Fellows

G. J. Hendricks
J. Jacobs
T. Sobota

Graduate Students

J. Budzinski
J. Hammer
J. D. Sterling
J. Yang
T. Zsak

5. INTERACTIONS WITH INDUSTRIAL AND GOVERNMENTAL GROUPS

Professor Culick continues collaboration with The Naval Weapons Center, having close contact with the work of Dr. K. Schadow and Dr. William Clark. In addition, he continues frequent exchange of information on combustion instability with groups at Wright-Patterson Air Force Base, Johns Hopkins Applied Physics Laboratory, and the McDonnell-Douglas Research Laboratory. Professor Culick is also serving as a member of the external advisory committee on the Shuttle boost rocket re-design.

Professor Marble serves as a member of the Air Force Studies Board, Committee on Hypersonic Technology for Military Applications and the Hypervelocity Mixing Advisory Group, NASA Langley Research Center. He also has close association with NASA Lewis Research Center on problems of turbomachinery, combustion and turbine cooling. In addition, he spends extended periods with the Gas Turbine Laboratory of the Massachussetts Institute of Technology. Professor Marble is Consultant to the Northrop Aircraft Division, TRW Inc. at the Norton Air Force Base, to the Rocketdyne Division of Rockwell International and to the Technical Systems Division, Aerojet General Corporation.

Professor Zukoski serves as an advisor and consultant to the U. S. Air Force on the problems of hydrogen combustion and explosion in the exhaust duct of the S.S.M.E. engine at the Vandenburg Satellite Launching Facility. He maintains contact with the Aero Propulsion Laboratory, Wright-Patterson Air Force Base concerning problems of ram jet and afterburner instability. Recently Professor Zukoski has been in contact with the Aerojet Technical Systems Division concerning their work on the NASP propulsion system.

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